

An Approach for the Design of Infrastructure Mode Indoor WLAN Based on Ray Tracing and a Binary Optimizer

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Abstract — This paper presents an approach that combines a ray tracing tool with a binary version of the particle swarm optimization method (BPSO) for the design of infrastructure mode indoor wireless local area networks (WLAN). The approach uses the power levels of a set of candidate access point (AP) locations obtained with the ray tracing tool at a mesh of potential receiver locations or test points to allow the BPSO optimizer to carry out the design of the WLAN. For this purpose, several restrictions are imposed through a fitness function that drives the search towards the selection of a reduced number of AP locations and their channel assignments, keeping at the same time low transmission power levels. During the design, different coverage priority areas can be defined and the signal to interference ratio (SIR) levels are kept as high as possible in order to comply with the Quality of Service (QoS) requirements imposed. The performance of this approach in a real scenario at the author's premises is reported, showing its usefulness.

Keywords: cost function, heuristic algorithms, indoor environments, particle swarm optimization, ray tracing, signal to interference ratio (SIR), wireless LAN

I. INTRODUCTION

Wireless Local Area Networks (WLAN) based on IEEE 802.11 access technology, also known as WiFi, have been widely deployed in recent years mainly due to the unlicensed character of their frequency bands of operation and the low cost of the equipment. However, this technology has a reduced number of non-overlapped channels and adequate planning before its deployment is advisable. This planning involves features concerning the number and location of the Access Points (APs), the channel assignment to these APs, the coverage and interference levels over the area of interest as well as parameters more directly related to the network performance, such as capacity and throughput. A review of different techniques used

to carry out the channel assignment in both centrally and uncoordinated managed WLAN can be found in [1].

In order to make an efficient use of the available resources avoiding at the same time a misleading view of the WLAN efficiency, the deployment of infrastructure mode WLAN in indoor scenarios, typically found in university campuses and large organizations, requires a thorough planning of the location and configuration for the APs taking into account the specific propagation characteristics of the environment along with certain QoS requirements.

Indoor WLAN planning problems are related to the indoor cellular planning, a field in which several early studies related to the optimization of indoor cellular systems have been published, e.g. [2-4]. However, in the WLAN case, the APs have transmitter powers which are usually fixed or limited to a reduced discrete set of values, use nearly omnidirectional antennas and have a short number of non-overlapped channels available. These features make the APs location choice and their channel assignment critical from the indoor WLAN design point of view due to the complex indoor environments. Different approaches can be found in the literature [5-23] specifically conceived for the optimized design of indoor WLAN.

In these works, several techniques have been used to account for the effect of different kinds of walls and geometrical details, which are critical to estimate signal levels or attenuation in indoor WLAN environments for planning purposes, ranging from empirical models like the two-ray-ground model corrected with fixed attenuations in walls and corners [22] or the COST 231 Multi-Wall Model [24], whose simplicity makes them appropriate for their combination with traffic models, to the most advanced ray tracing based techniques [25-28] that require a complete description of the physical and electrical characteristics of the environment and provide accurate results at the expense of much higher computational resources. Modified versions of ray launching or ray tracing approaches like the ones

presented in [29, 30] or methods that combine full wave analysis techniques with multiresolution formalisms like the Multi-Resolution Frequency Domain ParFlow (MR-FDPF) [31], have also been used for this purpose in the WLAN planning field.

Some of the optimization approaches proposed in the literature to solve the WLAN planning problem are briefly summarized in this paragraph. Simple search heuristics like the ones presented in [5] and [22] have been proposed to solve the problem: in [5] a simple sequential three-steps heuristic search method using priorities defined in terms of the received power, Signal to Interference Ratio (SIR) and transmitter densities to choose the best APs candidate locations and assign them non-overlapped channels is proposed, whereas in [22], the so called patching algorithm is used to simultaneously carry out the determination of a pre-defined maximum number of APs locations and their channel assignments driven by the system throughput and fairness, which are estimated using a traffic model. Integer Linear Programming (ILP) approaches, typically used for outdoor WLAN design [6], have also been considered to solve this kind of problems: for example in [7] different approaches are presented to solve the APs placement and their channel assignments using restrictions for minimum co-channel overlap, for channel interference or for both to maximize an experimentally derived throughput function from the downlink point of view. Non-Linear Integer Programming (NLIP) formulations to assign overlapped channels to a fixed number of access points with variable transmitter powers looking for the maximization of SIR levels at the test points have also been proposed [8] with an iterative solution procedure that uses the solution of the ILP problem presented in [9]. Hyperbolic and quadratic formulations [10-12] which are solved with the help of an initial greedy approach, used to build a feasible initial solution, followed by a local search stage to enhance the solution, have also been proposed for the optimized design of WLAN, maximizing aspects like the coverage, capacity, fairness, throughput or efficiency. In [13], the Evolution Strategy (ES) metaheuristic is used to obtain optimized WLAN designs with the minimum number of APs attending to user demand satisfaction in terms of either coverage or required throughput, with a view to distributing the resources as

uniformly as possible over the whole WLAN area. Genetic Algorithms (GA) based metaheuristics have often been used for this purpose [14-16]. For example, in [14] a GA based technique for the location of one AP for coverage area maximization based on attenuation is presented, in [15] GA are used to select the optimal locations of APs working in the same channel for real scenarios and a multi-objective GA (MOGA) is used in [16] to minimize the number of APs, select their locations and maximize the signal to noise ratio (SNR) over the whole WLAN area. Single- and multi-objective Tabu search have been used in [17, 18] to optimize the number, transmitter power and location of the APs in indoor WLAN with the help of constraints concerning coverage, interference and QoS, carrying out the channel assignment in a later step with a Tabu search algorithm [19]. Game Theory, [20, 21], has recently been proposed to tackle the optimized indoor WLAN design by gaming with the number, location and channel assignment of APs, the SIR and its balance, the traffic balance between different areas as well as the potential oversubscription of users to the different APs.

In this paper, a different approach that addresses the planning of indoor WLAN by carrying out the optimization of the most relevant parameters involved in it, most of them already considered in different ways in the works summarized in the previous paragraph, is presented. In short, the method combines a ray tracing technique [26, 27] with an optimizer based on a metaheuristic, the BPSO [32]. A basic version of this approach was previously introduced by the authors in [23] but it has now been improved and its capabilities extended. The approach consist of two independent steps. In the first place, the ray tracing technique is used to obtain the signal levels produced by a set of candidate APs locations in a uniform mesh of testing points defined over the area where the indoor WLAN is intended to be deployed. Next, these data are used to feed the BPSO optimizer in the search for a feasible WLAN configuration. Actually, the optimization takes into account the requirements for coverage and throughput in real scenarios and carries out the minimization of the required number of APs along with its power, the balance of the SIR,

the uniformity of the coverage or the priority of sites using a fitness function to sum up all these requirements and drive the search.

Concerning the metaheuristic BPSO, and despite the fact that the authors have a wide experience in the application of metaheuristics to other problems [33-37], this has been chosen as the optimization method because the discrete nature of the whole set of parameters to be tuned (number of active APs and their associated channels and transmission power) makes it appropriate to use of a binary representation based algorithm. Furthermore and unlike other metaheuristics such as GA, the number of operators, strategies and parameters to be tuned is far lower (the velocity operator in BPSO against selection, crossover and mutation strategies along with the crossover and mutation rates in the GA based schemes), making the tuning of the algorithm, as well as the tailored design of the cost or fitness function, easier, faster and reliable. In fact, taking into account that most of the computational cost of the approach is associated with the ray tracing step, the choice of the heuristic algorithm does not turn out to be a critical matter apart from its easiness of tuning. Regarding to the ray tracing method, the efficiency of the software used in this work has been achieved by using a combination of image theory and the binary space partitioning (BSP) algorithm, to analyze in an efficient way visibility relationships between the facets of the model for the intended scenario [26, 27].

In this paper, a brief review of the characteristics of both the ray tracing technique and the heuristic optimizer that have both been integrated in this approach for the WLAN design issue are presented in sections II and III, respectively. Section IV provides a description of the approach and Section V presents the fitness function developed to drive the search for solutions that best fit the restrictions imposed. A summary of results obtained for a realistic scenario are presented in Section VI and the key conclusions are outlined in Section VII.

II. THE RAY TRACING TECHNIQUE

The software tool CINDOOR, [26, 27] based on a full three-dimensional implementation of geometrical optics along with the uniform theory of diffraction (GO/UTD) that uses the image theory and the binary space partitioning (BSP) algorithm to implement an efficient technique that minimizes the computational cost, has been used in this work. The simulator provides either narrowband or broadband results useful for applications in mobile communications such as coverage maps, fading statistics, power delay profile, RMS delay, coherence bandwidth, etc.

This simulator allows the user to introduce the geometric description of the indoor scenarios by a set of flat plates, using either DXF files created with CAD applications or an incorporated geometry editor called GenCDB. In order to obtain an appropriate model of the scattered fields, besides the geometrical description of the environment, it is necessary to introduce the electromagnetic properties for any of the plates within the model: conductivity, dielectric constant as well as roughness. The coverage simulator also includes a database with materials usually found in buildings that can be modified and enlarged.

Although ray tracing is a technique that uses substantial computing resources, this software incorporates a significant improvement based on the BSP tree to re-arrange the flat plates of the geometrical model avoiding most intersection cross-checks along the different paths connecting the transmitter and the receiver. This idea of improving the efficiency of the ray launcher has been recognised by other authors [38-40].

In this work, the software simulator is used for computing the average power of the incoming signals provided by any of the potential APs at the receivers located at the test points. The APs are connected to 2.15 dBi lossless matched antennas, with the maximum configurable transmitting power and considered to

be located at a height of 3 meters. Moreover, the receivers are also considered to be connected to 2.15 dBi lossless matched antennas, located at the test points and at a height of 1.5 meters.

III. THE BINARY PARTICLE SWARM OPTIMIZER

The particle swarm optimization (PSO) technique is a population based stochastic metaheuristic whose continuous version was introduced in [41], followed in [32] by its binary version. Basically, the PSO mimics the behavior of swarms of individuals like bird flocks or fish schools and it can be used to solve optimization problems. In this work, given the discrete nature of the parameters involved in the optimization process, the binary version of the PSO algorithm (BPSO) has been considered.

In the BPSO optimizer [32], each one of the particles within the swarm (or population) represents a potential solution to the problem at hand. During the optimization process, each particle, i , is characterized by N -dimensional velocity and position vectors $v_i=(v_{i1},\dots,v_{iN})$ and $x_i=(x_{i1},\dots,x_{iN})$, respectively, in which N corresponds with the number of dimensions of the search space. The movement of each particle at each iteration, k , is conditioned by its current state ($v_i(k)$, $x_i(k)$), its memory or best position ever achieved by that particle, $p_i=(p_{i1},\dots,p_{iN})$, and the best solution ever found by the whole set of particles, $g=(g_1,\dots,g_N)$, according to the following expressions used in this work:

$$v_{in}(k+1) = \text{sign}(\bar{v}_{in}(k+1)) \cdot \min(|\bar{v}_{in}(k+1)|, 4) \quad (1)$$

$$x_{in}(k+1) = \begin{cases} 1 & S(v_{in}(k+1)) > \text{rand}_3 \\ 0 & \text{otherwise} \end{cases} \quad (2)$$

where

$$\bar{v}_{in}(k+1) = v_{in}(k) + 2\text{rand}_1[p_{in}(k) - x_{in}(k)] + 2\text{rand}_2[g_n(k) - x_{in}(k)] \quad (3)$$

and

$$S(v) = \frac{1}{1 + e^{-v}} \quad (4)$$

In (1)-(3), $v_{in}(k)$ and $x_{in}(k)$ represent the n -th dimension of the velocity and position for the i -th particle at the k -th iteration. Moreover, $rand_1$, $rand_2$ and $rand_3$ are uniform distributed random numbers in the interval $[0, 1]$, used to model the stochastic behavior of the population. Finally, in (4) $S(v)$ represents the sigmoid function, used as a probability threshold. In this work, a global asynchronous version of the optimizer has been considered as it is more efficient for a serial implementation. Moreover, a tournament selection strategy similar to the one used in genetic algorithms based optimizers has been introduced in order to speed up the convergence in the initial stages of the optimization, keeping at the same time diversity among particles.

This iterative procedure, more detailed in [23], is driven by a fitness function that must be conceived in such a way that it represents with a high degree of fidelity the problem to solve as well as the restrictions imposed on it, because it constitutes the only link between the physical problem and the optimizer.

IV. DESCRIPTION OF THE APPROACH

Basically, the approach presented in this work uses the signal levels produced by the set of candidate APs at any of the receiver locations or test points, which are uniformly distributed over regular meshes covering the areas of interest, and that are computed with the help of the ray tracing method, to feed the BPSO optimizer and start the search for a feasible infrastructure mode WLAN configuration that satisfies the coverage and SIR requirements at the test points. As a consequence, apart from the signal levels obtained with the ray tracing method, the approach requires additional information concerning the set of powers that can be configured at the APs, the noise level of the receivers considered for the test points and the specific settings selected for the WLAN including the available non overlapping channels and the transmission rate

that defines the sensitivity and SIR thresholds necessary to provide a certain QoS according to the IEEE 802.11 standard [42].

In order to achieve this goal, the optimizer is allowed to handle the following aspects: the choice of APs amongst a set of potential sites, the non-overlapped channel assignment to those active APs and their transmission power from the configurable set of possibilities. The search is driven towards the selection of the lowest number of APs locations with the lowest configured power but keeping at the same time coverage and SIR values as high as possible in order to comply with the QoS requirements.

Moreover, the possibility of assigning different levels of priority to different areas of the region of interest has been included by incorporating the capability of setting to every test point a priority defined in ascending order by means of an integer number in the range $[1, N_{prior}]$. The assigned priorities force with the fitness function and throughout the optimization process to fulfill the restrictions gradually in descending order, focusing first on those test points with the highest priority and later on the remaining test points with less priority.

A lower limit for the required number of APs is used in order not to waste computational resources unnecessarily. This limit comes given by the following rough estimation:

$$N_{AP\min} = \frac{T_{req} \rho N_{users}}{T_{AP}} \quad (5)$$

in which T_{req} represents the traffic in Mbps that is intended to be assigned to the users, N_{users} , ρ indicates the using factor of the T_{req} parameter and T_{AP} is the transmission rate in Mbps that provides every AP.

According to the metaheuristic nature of the population based BPSO algorithm, it is required to evaluate the fitness function for every particle at each iteration and thus, the interaction in a direct way between the

optimizer and the simulator becomes unviable. The only way to overcome this limitation is to use first the simulator to compute and store the signal levels received at any of the test points from all the proposed locations for the APs in all the available channels. Later on, this information is properly processed to account for the different available powers at the APs and stored in an appropriate data structure used by the optimizer.

Furthermore, due to the binary nature of the optimizer, the description of the features of the APs is coded for each one using an initial bit working as a flag and representing whether the current AP is on or off, a second group with a minimum length that depends on the WLAN configuration that indicates the current channel assigned at that iteration to that AP, as well as a third group with a minimum length that depends on the number of levels of power available for the APs and that encodes those levels and identifies the value chosen for the current AP at that iteration of the optimization process. The complete binary sequence with the codes of the whole set of APs makes up the so called position of the N-dimensional particle in the optimizer, $x_i = (x_{i1}, \dots, x_{iN})$.

At each iteration of the optimization process, which is driven by the fitness function described in detail in the next section, the analysis of the quality of any particle or potential solution within the swarm is carried out using the data structure previously computed.

Any of the test points can be marked as covered with every configuration of the WLAN associated with each particle if and only if it is verified that at that location the thresholds established for the power are exceeded and the criteria concerning the SIR are met for the whole set of incoming signals from the active APs, taking as reference the strongest one and neglecting the signals with levels below the receiver's noise level. From these basic parameters, the different terms that make up the fitness function can be assessed, focusing mainly on achieving the highest coverage and the lowest level of interference by switching on as

few APs as possible (always higher than the value of N_{APmin} in (5)) and, at the same time, taking care of providing service at any of the areas inside the scenario according to their priority, meeting the sensitivity and SIR thresholds imposed and choosing APs transmission power as low as possible to improve energy savings.

V. THE FITNESS FUNCTION

The fitness function constitutes the only link between the optimizer and the physical problem at hand and it has to contain all the information needed to drive the search. A fitness function designed to optimize coverage for indoor infrastructure mode WLAN considering AP placement selection along with channel assignment under fixed transmitting power conditions subject to restrictions concerning the signal to interference ratio was presented in a previous work by the authors [23]. In this work, and taking as the starting point the previous one, a new fitness function has been developed that, in addition to the optimal APs location and channel assignment selection from a set of potential sites, allows the minimization of AP transmitter powers and the definition of different priority coverage areas, all of them features of practical interest for the design of WLAN.

The new fitness function to be minimized consists of eight different terms:

$$F = \omega_1 N_{on} + \omega_2 N_{co} + \omega_3 (1 - A_{SIR}) + \omega_4 (1 - Cov) + \omega_5 (1 - U_{cov}) + \omega_6 (1 - Prior) + \omega_7 P_{sum} + \omega_8 (1 - A_{pow}) \quad (6)$$

where the coefficients ω_1 to ω_8 define the weights assigned to each component of the fitness function.

In (6), the parameter N_{on} accounts for the number of active APs and is given by

$$N_{on} = \sum_{i=1}^{N_{AP}} S_i \quad (7)$$

in which N_{AP} represents the number of proposed APs locations and S_i takes the value 0 or 1 depending on the state (off/on) of the i -th proposed AP location.

The parameter N_{co} accounts for the number of interference lines (couples of active APs with the same channel assignment), and comes given by

$$N_{co} = \sum_{i=1}^{N_{on}} \sum_{j=i+1}^{N_{on}} co_{ij} \quad (8)$$

with co_{ij} (channel overlap) taking the value 1 when channels assigned to APs i and j are equal and 0 otherwise. It will always take values higher than or equal to one for more than three active APs.

The two terms in (6) associated with these two last parameters will be the predominant ones in the search of the minimum and are assigned equal weights, $\omega_1 = \omega_2 = 0.5$, giving the same relevance to the number of active APs and the uniform distribution of channels over the WLAN.

In the third term in (6), A_{SIR} gives an idea about the average signal to interference ratio in the whole set of receiving positions, N_{Rx} . It is normalized with respect to the product of the maximum SIR value over the whole set of test points and the number of them in order to obtain a zero value of this third term in case uniform SIR values are obtained in the whole WLAN. The A_{SIR} term, given in terms of the SIR levels at the i -th receiving test point, SIR_i , takes the following value:

$$A_{SIR} = \frac{1}{N_{Rx} SIR_{\max}} \sum_{i=1}^{N_{Rx}} SIR_i \quad (9)$$

The fourth term in (6), which takes the value 0 when the whole set of test points are covered, deals with the level of coverage obtained over the whole set of test points in terms of the coverage parameter for each receiving point, cov_i , which takes the value 1 if the point satisfies the coverage and SIR specifications and 0 otherwise. The parameter Cov is given by

$$Cov = \frac{1}{N_{Rx}} \sum_{i=1}^{N_{Rx}} cov_i \quad (10)$$

With regard to the fifth term in (6), it is obtained from Jain's formula [43] and is introduced as a metric to measure the uniformity of the coverage achieved by the distribution of the active APs proposed by the optimizer. The parameter U_{cov} in (11) takes the value 1 only when all APs provide coverage to the same number of test points, i.e. the maximum coverage uniformity is achieved. Moreover, AP_i indicates the i -th active AP, c_j represents the active AP serving the j -th test point, and the δ function takes the value 1 when both AP_i and c_j are equal.

$$U_{cov} = \frac{1}{N_{on}} \frac{\left(\sum_{i=1}^{N_{on}} \sum_{j=1}^{N_{Rx}} \delta(AP_i - c_j) \right)^2}{\sum_{i=1}^{N_{on}} \left(\sum_{j=1}^{N_{Rx}} \delta(AP_i - c_j) \right)^2} \quad (11)$$

The sixth term in (6) provides the optimizer with the information needed to initially cover the regions with a higher priority (N_{prior} , set to a value of 5 in this work) and the rest of regions in a descending order of priority. The value of the parameter $Prior$ is obtained from the following expression:

$$Prior = \frac{\sum_{j=1}^{N_{prior}} \left(1 + \frac{\sum_{i=1}^{N_{Rx}} \delta(p_j - p_i) cov_i}{\sum_{i=1}^{N_{Rx}} \delta(p_j - p_i)} \right) \left(2^{(p_j-1)} \cdot 100 \right)}{\sum_{j=1}^{N_{prior}} 2^{p_j} \cdot 100} \quad (12)$$

where p_i represents the priority value assigned to the i -th test position, p_j the j -th priority value considered, $\delta(p_j - p_i)$ takes the value 1 when p_j equals p_i and 0 otherwise. This parameter can take a maximum value of 1 that involves a null contribution of this term to the fitness function in case all the test points are covered according to the restrictions imposed.

The seventh term in (6) is used to minimize the power assigned to each active AP among the set of possibilities considered. It is given by:

$$P_{sum} = \frac{\sum_{i=1}^{N_{on}} P_{APi}}{P_{APmax}} \quad (13)$$

in which P_{APi} represents the power assigned to the i -th active AP and P_{APmax} is the value of the total maximum configurable power for the N_{on} active APs.

Finally, concerning the last term in (6), the parameter A_{pow} is used to measure the average power provided by the configuration proposed by the optimizer at the test points. This parameter makes it possible to keep alive the optimization process when each active AP has non interfering channels assigned and the SIR does not provide a measure of the system performance. Additionally, it allows the APs placement to be chosen in such a way that the power available at the test points is maximized. A_{pow} comes given by

$$A_{pow} = \frac{\sum_{i=1}^{N_{Rx}} \sum_{j=1}^{N_{on}} \delta(AP_j - c_i) P_{cij}}{N_{Rx} \max(P_{cij})} \quad (14)$$

where AP_j indicates the j -th active AP, c_i represents the active AP serving the i -th test point, P_{cij} the power provided by the j -th active AP at the i -th test point, the δ function takes the value 1 when both AP_j and c_i are the same and $\max(P_{cij})$ indicates the maximum value of the power provided by active APs at the test points.

The parameters ω_3 to ω_8 are used to balance the search for the minimum taking into account the different aspects introduced previously in (9)-(14). Their associated terms always take values lower than 1, becoming 0 when restrictions are fulfilled. Taking this into account, the following conditions have been imposed on the coefficients in order to make it feasible to tune the last set of parameters:

$$\sum_{i=1}^2 \omega_i = 1 \quad \text{and} \quad \sum_{i=3}^8 \omega_i = 1 \quad (15)$$

The tuning of the last six weights (ω_3 to ω_8) has been carried out considering different scenarios and focused on global objectives related to minimizing the number of active APs, their associated transmission

powers along with the interference at the test points, according to the coverage priorities. Their tuned values are the following: $\omega_3=0.25$, $\omega_4=0.2$, $\omega_5=0.17$, $\omega_6=0.3$, $\omega_7=0.04$ and $\omega_8=0.04$. In spite of the fact that the tuning procedure is not explicitly demonstrated here, a brief justification of the choice of such values is given below. Basically, the two first terms in (6) allow the optimization procedure to provide coverage to the whole area during the initial iterations by increasing the number of active APs and the number of coupling lines between them and then, forced by the rest of the terms in (6), lead directly to the minimization of their values. In order to comply with the requirements, it is necessary to provide coverage (in terms of both signal and SIR) to the different areas in descending order of priority but keeping at the same time similar SIR levels throughout the area. For this reason, a similar importance must be assigned to coefficients ω_3 , ω_4 and ω_6 , with a prevalence of the priority over coverage and SIR. Even though the uniformity of coverage plays an important role in the process, the criterion must be relaxed in order to allow the variations of area served by the different active AP as a consequence of the variations in transmission power and this is performed by reducing its impact on the fitness function by choosing a constant ω_5 slightly lower than the previous ones. Finally, taking into account that the configured power for the active APs has a significant impact on the whole set of previous parameters, the two weights related to it must have a far lower impact over the fitness function to avoid erratic behaviors of the optimizer and at the same time to keep alive the process when the other conditions are nearly satisfied, allowing the minimization of the number of active APs and their configured power. Both ω_7 and ω_8 drive the search towards the solution once the coverage conditions are fulfilled. Starting from these premises, and after analyzing the behavior of the optimizer in different scenarios, a fine tuning of the parameters ω_3 to ω_8 leads to the values already presented and allows the design of the indoor WLAN.

VI. RESULTS

To demonstrate the usefulness of the approach proposed, a real scenario has been considered: the Ingeniería de Telecomunicación “Profesor José Luis García García” building at the University of Cantabria, which takes up an area of approximately 90x61m, with two main three and two floors buildings connected through the lower floor. The 3D model of the four floors is shown in Figure 1. Most of the spaces in the building are offices and laboratory rooms that require WLAN access. The WLAN to be optimized uses the non-overlapped channels 1, 6, and 11 of the 2.4GHz band. The APs can be configured to operate with powers of 30, 20, 10, 5 and 1mW. A WLAN configuration with a transmission rate of 36Mbps is considered, involving a receiver sensitivity of -75dBm and a minimum SIR of 20dB. The rough estimation for N_{APmin} in (5) with $T_{req}=1\text{Mbps}$, $\rho=1$ and $T_{AP}=36\text{Mbps}$, gives a minimum number of 5 APs which is taken as the lower limit for the optimization process.

Figure 2 shows the plan view of the buildings. A priority level of 5 has been assigned to those areas that require WiFi service in order to try to strengthen their coverage against other less important areas whose priority has been set to 1. Areas with priority 5 are shown with a gray shadowing. Areas outside the buildings have not been considered during the optimization. Uniform grids consisting of 6000 test points or locations for the receivers have been defined for each floor and building with spatial resolutions in the range [48, 90] cm, depending on the floor. Furthermore, a height of 1.5m has been considered for the receivers.

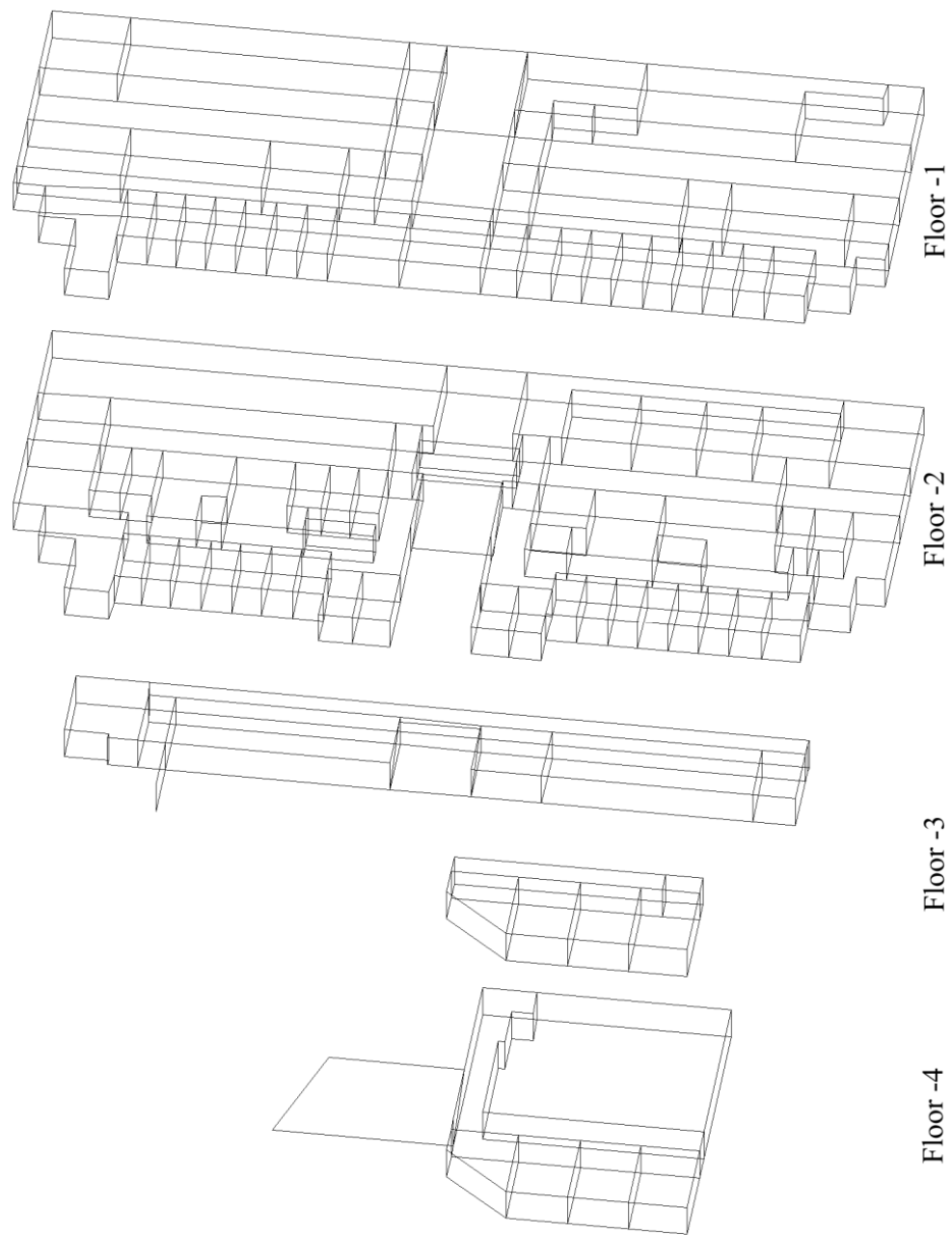
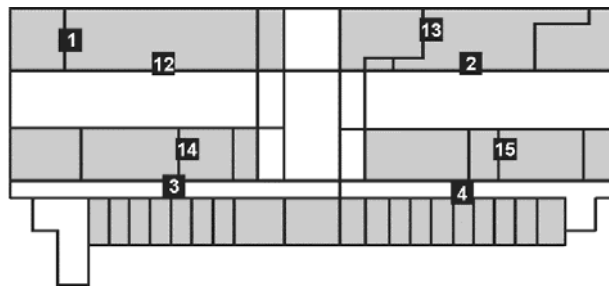


Figure 1. 3D model of the building analyzed.



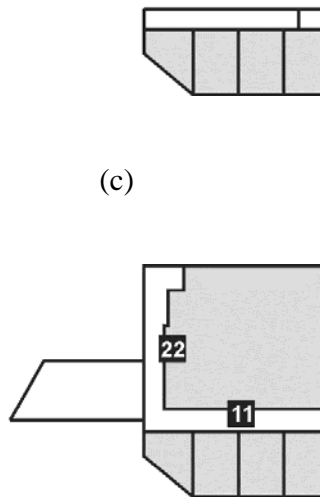
(a)



(b)



(c)



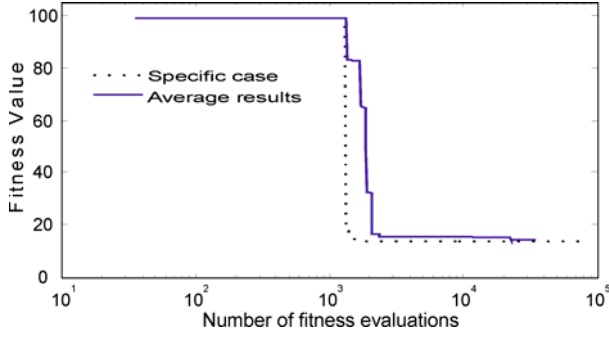
(d)

Figure 2. Plan view showing priority 5 and 1 areas in gray and white, respectively. The approximate location of the 22 APs is also shown. (a) Floor -1, (b) Floor -2, (c) Floor -3, (d) Floor -4.

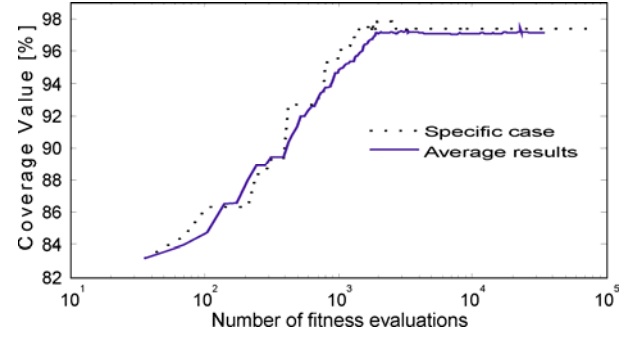
The initial random proposal with 22 APs locations distributed over the four floors of the building is also shown in Figure 2, in which the approximate location for all the APs is identified with the numbered squares. The APs are placed at a height of 3m.

Using these data along with the data structure obtained from them and the signals levels provided by the ray tracing simulator, the optimizer can be launched to meet a certain coverage limit. In this example, a requirement of 97% of coverage has been considered.

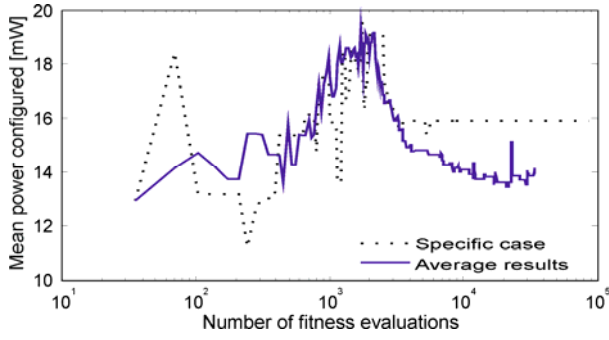
The heuristic nature of the optimizer along with the non-uniqueness of the solution makes it necessary to carry out first a brief study concerning the average behavior of the optimizer based on a set of independent runs. For this purpose, ten independent runs have been considered and Figure 3(a)-(d) show in continuous line the averaged results obtained concerning the convergence of the fitness function, the mean coverage, and the mean power configured at the APs and the number of active access points. It can be noticed how the optimizer focuses, at the initial iterations, on improving the overall coverage (see Figure 3(b)) by increasing the number of active APs (see Figure 3(d)) and their configured power (see Figure 3(c)), and once the coverage goal is achieved (in this case after approximately two thousand iterations have elapsed), the focus transfers to the decrease of the number of APs and their configured power. If the optimizer is launched more than once, alternative solutions that might be more appropriate for different reasons (accessibility, maintenance, etc) can be obtained due to the open solution nature of the problem, and some advantage can be taken from this fact from the WLAN design point of view.



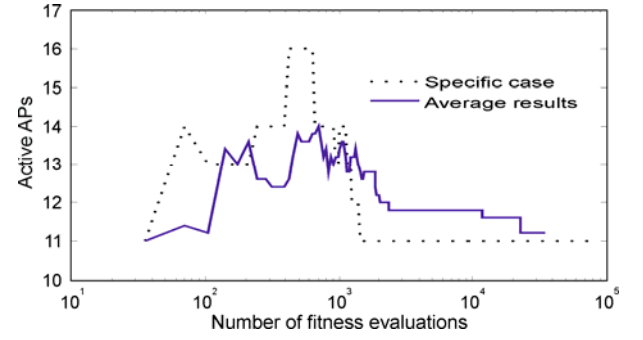
(a)



(b)



(c)



(d)

Figure 3. Behavior of the optimizer. Evolution of different parameters for both the average of ten independent runs (continuous line) and a specific case (dash-dotted line): (a) Fitness evolution, (b) Coverage evolution, (c) Evolution of the mean power configured at the APs, (d) Mean number of active APs evolution.

A more detailed description of the results achieved is summarized in Table 1 for five out of the ten representative independent runs included in the analysis. For the five configuration sets, information including both the assigned channel and the transmitting power for every active AP on each floor is provided. First of all, it should be noted that the metaheuristic nature of the optimizer provides the user with a set of quite different configurations depending on the initial seed but, at the same time, all of them

have a similar overall accuracy in terms of the residual fitness value. This makes it possible for users to choose that configuration that best meets their preferences or needs.

Settings		Configuration 1		Configuration 2		Configuration 3		Configuration 4		Configuration 5	
Floor	AP	CH	P	CH	P	CH	P	CH	P	CH	P
-1	1	-	-	-	-	1	10	-	-	-	-
	2	-	-	1	5	6	20	11	10	11	10
	3	1	20	-	-	11	20	-	-	-	-
	4	-	-	-	-	-	-	-	-	-	-
	12	6	10	1	10	-	-	6	20	1	20
	13	11	30	-	-	-	-	-	-	-	-
	14	-	-	6	20	-	-	1	20	6	5
	15	6	20	11	20	1	20	6	10	6	20
-2	5	1	10	6	5	6	5	1	5	11	1
	6	11	10	-	-	11	10	-	-	1	10
	7	11	5	11	10	1	20	11	5	-	-
	8	6	5	6	20	-	-	1	20	6	5
	16	-	-	-	-	-	-	-	-	1	10
	17	-	-	11	10	-	-	6	10	6	5
	18	-	-	-	-	-	-	-	-	11	10
	19	-	-	-	-	6	10	-	-	-	-
-3	9	6	30	6	20	6	10	-	-	6	10
	10	1	30	1	20	11	20	-	-	1	20
	20	-	-	-	-	-	-	1	20	-	-
	21	-	-	-	-	-	-	-	-	-	-
-4	11	11	5	11	5	-	-	11	20	11	5
	22	-	-	-	-	1	1	6	20	-	-

Table 1. Configuration of the APs for the case presented. For every AP, “CH” represents the final assigned channel, “P” is the power configured in mW, and “-” means that it is off.

It must be pointed out that the “Configuration 1” in Table 1 corresponds with the specific case shown in Figure 3. Focusing on that specific case, from the results obtained, it can be noticed that four APs are switched on in floors -1 and -2, two in floor -3 and one in floor -4. This last AP, helped by the two non-overlapped channel APs in floor -3, provides coverage for the -3 floor of the second building. Results for the fitness, coverage, mean power configured and number of active APs for this case are shown with a dotted line in Figure 3(a)-(d). The iterative process has been intentionally extended to show no further evolution of this solution. From these results it is obvious that after focusing on improving coverage by increasing the mean power and the number of active APs, the optimizer puts its efforts into the minimization of the number of access points and their associated mean configured power, which decrease to eleven and reach approximately 16 mW at the end of the optimization, respectively.

Finally, Figure 4 shows the coverage and SIR maps for this last case. Non covered areas are shown in black, although they can be easily identified as they appear isolated from regions with lower SIR levels. It can be observed that the approach proposed has been able to keep SIR values above the required 20 dB threshold level in almost all of the building locations, obtaining the lowest SIR values in areas with lower priority, except in some small regions shown in black which are located close to the walls in most cases. It can also be noticed that the optimizer has managed to infer itself that the AP 11 in the -4 floor along with the non-overlapped channel APs 9 and 10 in the -3 floor are able to provide coverage to the -3 floor of the second building.

VII. CONCLUSIONS

An approach for the optimization of infrastructure mode indoor WLAN from the downlink point of view has been presented in this paper. The approach uses as input data the signal levels of a pool of proposed APs locations at a mesh of testing points over the area of interest, computed by a ray tracing tool, along

with a binary version of the particle swarm optimizer (BPSO) used to obtain a WLAN proposal to meet the requirements of a certain level of coverage (97% for the cases shown) over the scenarios analyzed. The approach chooses a minimum number of AP locations along with their associated channels and configured transmitting powers, using as the main search driving element a fitness function that takes into account different characteristic parameters of the WLAN.

The results included demonstrate the capabilities of the approach that could be helpful in the indoor WLAN design phase, prior to its deployment. Alternative WLAN proposals can be obtained by simply running again the optimization procedure due both to the stochastic nature of the optimizer and the non-deterministic nature of the problem solution.

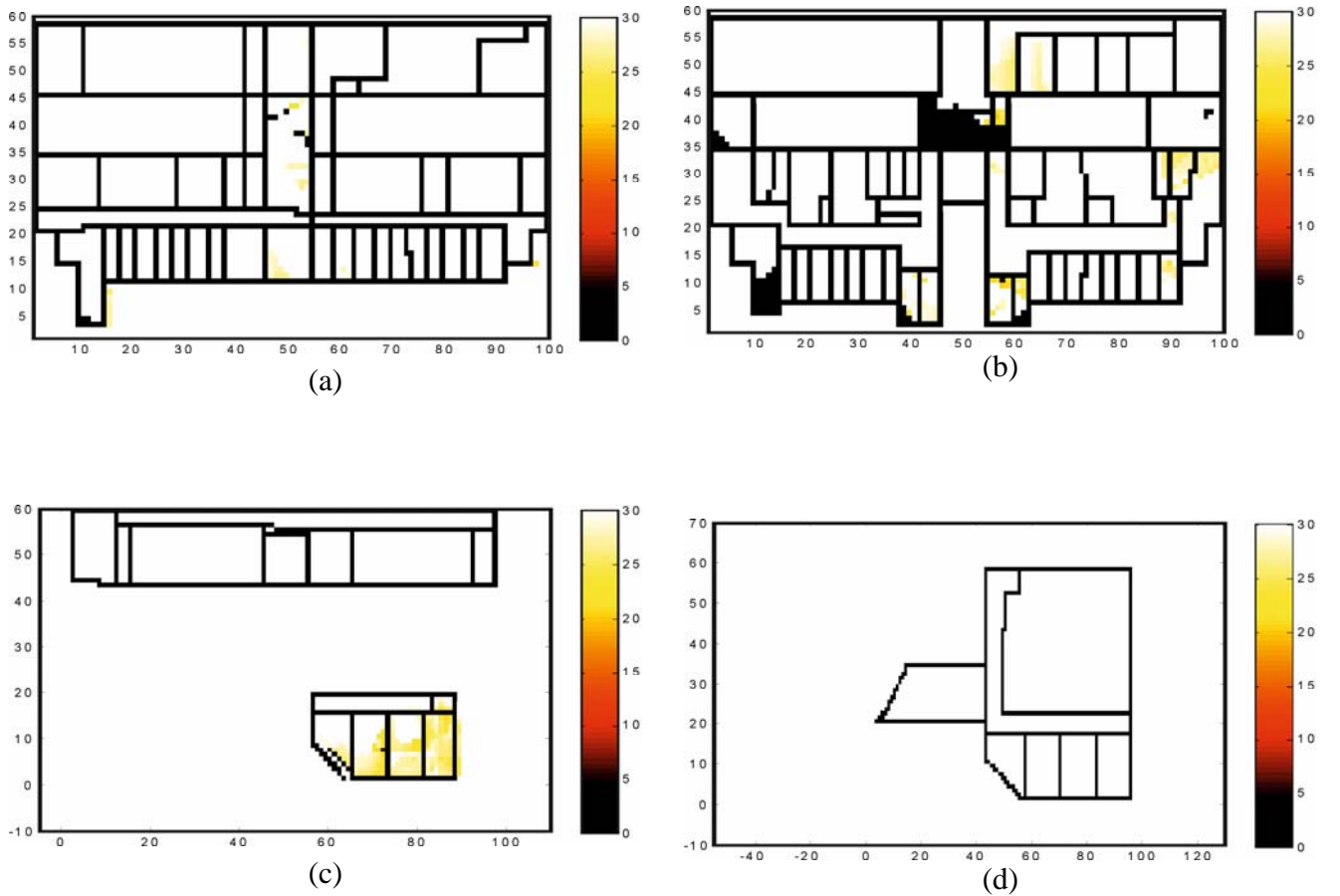


Figure 4. SIR level in dB and coverage maps. (a) Floor -1, (b) Floor -2, (c) Floor -3, (d) Floor -4.

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